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Emergence of long-range angular correlations in low-multiplicity proton–proton collisions

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Abstract

This Letter presents the measurement of near-side associated per-trigger yields, denoted ridge yields, from the analysis of angular correlations of charged hadrons in proton–proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$. Long-range ridge yields are extracted for pairs of charged particles with a pseudorapidity difference of $1.4 < |\Delta\eta| < 1.8$ and a transverse momentum of $1 < p_{\mathrm{T}} < 2\,\mathrm{GeV}/c$, as a function of the charged-particle multiplicity measured at midrapidity. This study extends the measurements of the ridge yield to the low multiplicity region, where in hadronic collisions it is typically conjectured that a strongly-interacting medium is unlikely to be formed. The precision of the new results allows for the first direct quantitative comparison with the results obtained in $\mathrm{e^+e^-}$ collisions at $\sqrt{s} = 91\,\mathrm{GeV}$, where initial-state effects such as pre-equilibrium dynamics and collision geometry are not expected to play a role. In the multiplicity range where the $\mathrm{e^+e^-}$ results have good precision, the measured ridge yields in pp collisions are substantially larger than the limits set in $\mathrm{e^+e^-}$ annihilations. Consequently, the findings presented in this Letter suggest that the processes involved in $\mathrm{e^+e^-}$ annihilations do not contribute significantly to the emergence of long-range correlations in pp collisions.

*See Appendix A for the list of collaboration members

Long-range angular correlations have been observed in the collisions of ultra-relativistic heavy ions both at RHIC [1–4] and LHC [5–7]. In such collisions, the presence of correlations between pairs of particles with large pseudorapidity differences is interpreted as a signature for the existence of a strongly-coupled medium, known as the quark–gluon plasma (QGP), which converts the initial pressure gradients created in non-central nucleus–nucleus collisions into a collective momentum anisotropy of the final-state hadrons. In particular, the collectivity signal manifests itself as a near-side ridge around the jet fragmentation peak in the two-particle correlation function, indicating the presence of a medium with considerable anisotropic flow.

Long-range correlations have also been observed in high-multiplicity proton–proton (pp) [8–12], proton–nucleus (pA) [13–16], and light nucleus–nucleus collisions [17, 18]. These results have challenged the interpretation of the so-called collective phenomena in hadronic collisions, and raised the question whether the same underlying dynamics can be responsible for the emergence of long-range correlations in small and large systems [19]. Notably, the formation of a medium and its subsequent evolution, which is understood to take place in heavy-ion collisions might not be justifiable in small collision systems, where the requirement of thermal equilibrium may not be achieved under the conditions of small system size. Despite a vast experimental and theoretical effort, an unambiguous description of these experimental data is not yet achieved [20–22], although there has been recent progress [23–25]. Flow-like signatures could indeed originate from the very early stages of the collisions [26, 27] or develop during the late stages of the collisions as a consequence of the interaction with a strongly-coupled medium [28, 29]. This suggests that ridge measurements combined with measurements of jet shape modification can eventually be used to separate initial state and flow-driven contributions [30].

Recently, new experimental insights have been obtained by the study of long-range correlations in e^+e^- collisions at $\sqrt{s} = 91\,\mathrm{GeV}$ using ALEPH [31] archived data [32]. Collisions between point-like electrons and positrons remain unaffected by the presence of beam remnants or gluonic initial-state radiation, and are not sensitive to the modeling of parton distribution functions [33, 34]. Near-side ridge is neither observed in the lab reference frame nor in the thrust-axis reference frame. The results obtained in e^+e^- collisions were also compared with the associated yield measurement in pp collisions with CMS [35, 36], but due to the large uncertainties of the existing pp measurement, a statistically significant comparison between the ridge yields measured in pp and e^+e^- collisions was not feasible. A systematic study of such signatures across collision systems and sizes represents a unique opportunity to characterize the emergence of collective phenomena. In particular, measurements performed in pp collisions with very low multiplicity can provide crucial inputs to address the relevance of initial-state effects [28] in the presumed absence of a flow-inducing medium and final-state correlations [37, 38], and in turn constrain the magnitude of these effects traditionally afflicted by a large uncertainty [39]. At the same time, comparing to the e^+e^- collision system helps to identify physical processes in the pp system that do contribute to collectivity, as no such signals were detected in the e^+e^- system [32].

In this Letter, the near-side long-range yields are measured in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ with good precision down to very low multiplicities. The results are reported for pairs of charged particles with pseudorapidity $1.4 < |\Delta\eta| < 1.8$ and transverse momentum $1 < p_{\mathrm{T}} < 2\,\mathrm{GeV}/c$, as a function of the charged-particle multiplicity measured at midrapidity. The experimental precision of this study allows for the first quantitative comparison with the results obtained in e^+e^- collisions at $\sqrt{s} = 91\,\mathrm{GeV}$ with ALEPH archived data, where initial-state effects are not expected to play a role. The measurement is also compared to predictions of PYTHIA 8.3 [38] and EPOS LHC simulations [40].

The data were collected in 2017 and 2018 using the ALICE apparatus [41] at the LHC. Information about the detector configuration and performance can be found in Refs. [42, 43]. The main systems used for this study were the central-barrel detectors, located within a solenoidal magnet and used for charged-particle tracking. These include the Inner Tracking System and the Time Projection Chamber. The V0 detector, consisting of two scintillator arrays located at pseudorapidities of $2.8 < \eta < 5.1$ and

$-3.7 < \eta < -1.7$, was used for the trigger and event selections. Minimum-bias (MB) events were selected online by requiring a signal from at least one charged particle in both V0 counters. The analyzed data sample consists of about 1.3 billion MB pp collisions at a center-of-mass energy of $\sqrt{s} = 13\,\mathrm{TeV}$ within primary vertex range $z_{\rm vtx} < 8.0\,\mathrm{cm}$ along the beam axis, corresponding to an integrated luminosity of about $22\,\mathrm{nb}^{-1}$.

The observables presented in this analysis are extracted using two-particle angular correlations for pairs of charged particles. The two-particle per-trigger yield is measured as a function of relative azimuthal angle $\Delta\varphi$ and pseudorapidity $\Delta\eta$ of two particles – traditionally called trigger and associated – and is defined as

$$\frac{1}{N_{\rm trig}}\frac{\mathrm{d}^2N_{\rm pair}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\varphi} = B(0,0)\frac{S(\Delta\eta,\Delta\varphi)}{B(\Delta\eta,\Delta\varphi)}. \tag{1}$$

Eq. (1) is evaluated within a range of transverse momentum of the trigger ($p_{\rm T,trig}$) and associated ($p_{\rm T,assoc}$) particles within $|\eta| < 1.0$ where $p_{\rm T,trig} > p_{\rm T,assoc}$. The total number of trigger particles is denoted with $N_{\rm trig}$, and the number of trigger and associated particle pairs with $N_{\rm pair}$. This two-particle yield $S(\Delta\eta,\Delta\varphi)$ is corrected for pair acceptance and reconstruction effects by constructing a mixed-event distribution $B(\Delta\eta,\Delta\varphi)$ from pairs where the trigger and associated particles are taken from different events. This mixed-event distribution is normalized by $B(0,0)$ computed by pairs of like-sign particles traveling in the same direction for which acceptance and reconstruction effects are identical by construction. The event mixing is performed such that events with similar multiplicity and primary vertex $z_{\rm vtx}$ (bins of 2 cm) are combined. The final per-trigger yield is obtained by averaging over these individual bins. In addition, all tracks are corrected for the single-particle tracking efficiency as a function of $p_{\rm T}$ and η. The efficiency corrections and acceptance factors are obtained by simulating events with PYTHIA 8.3 with the Monash tune [44], and the detector response simulated using the GEANT3 transport package [45].

The per-trigger yield distribution as a function of $\Delta\varphi$ is obtained by integrating the two-dimensional two-particle per-trigger yield in the long-range intervals $1.4 < |\Delta\eta| < 1.8$, in order to exclude the region dominated by the jet fragmentation peak

$$Y(\Delta\varphi) = \frac{1}{N_{\rm trig}}\frac{\mathrm{d}N_{\rm pair}}{\mathrm{d}\Delta\varphi} = \int_{1.4<|\Delta\eta|<1.8}\left(\frac{1}{N_{\rm trig}}\frac{\mathrm{d}^2N_{\rm pair}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\varphi}\right)\frac{1}{\delta_{\Delta\eta}}\mathrm{d}\Delta\eta, \tag{2}$$

where $\delta_{\Delta\eta} = 0.8$ is the normalization constant for the chosen $\Delta\eta$ range. The ridge yield $Y^{\rm ridge}$ is extracted by integrating the near-side area of the associated per-trigger yield using

$$Y^{\rm ridge} = \int_{|\Delta\varphi|<|\Delta\varphi_{\rm min}|} Y(\Delta\varphi)\mathrm{d}\Delta\varphi - 2|\Delta\varphi_{\rm min}|C_{\rm ZYAM}. \tag{3}$$

A Zero-Yield-At-Minimum (ZYAM) procedure is applied to subtract the baseline of the per-trigger yield. We assume that $Y(\Delta\varphi)$ has an uncorrelated flat contribution, $C_{\rm ZYAM} = Y(\Delta\varphi_{\rm min})$, where $\Delta\varphi_{\rm min}$ is the location of the minimum of $Y(\Delta\varphi)$. To reduce the impact of statistical fluctuations, $Y(\Delta\varphi)$ is fitted by a symmetric Fourier series up to third harmonic $F(\Delta\varphi) = \sum_{n=0}^{3} 2a_n\cos(n\Delta\varphi)$, which is found to be adequate for a precise extraction of $\Delta\varphi_{\rm min}$ and $C_{\rm ZYAM}$. This procedure is illustrated in the right panel of Fig. 1. Since the fit is only used to locate the bounds of the near-side ridge, the impact of the higher harmonics on the baseline and ZYAM procedure is negligible. The ridge yield provides a measure for collective effects, and is generally compatible with the measurements of flow coefficients v_n in small systems [46]. The measurement of $Y^{\rm ridge}$ also facilitates the comparison with the readily available $\mathrm{e}^+\mathrm{e}^-$ result, and does not suffer from ambiguities related to low-multiplicity template subtraction applied in other measurements [15].

The analysis is performed in different intervals of measured multiplicity. In order to determine the corrected charged-particle multiplicity $\langle N_{\rm ch}\rangle$ in each multiplicity interval, the number of charged tracks is counted within $|\eta| < 1$ and $p_{\mathrm{T}} > 0.2\,\mathrm{GeV}/c$. This number is corrected for detector effects by correlating reconstructed and simulated multiplicities, and randomly sampling a new multiplicity value from the simulated distribution corresponding to the reconstructed value. At the same time, the resampling technique reduces self-correlation between the multiplicity and the particles entering the per-trigger yield. The analysis is carried out for 14 multiplicity intervals, ranging from $N_{\mathrm{ch}} = 0$ to 62, where the average MB multiplicity is about 11.3.

The systematic uncertainties of the ridge yields are evaluated by varying the event and track selections as well as the integration ranges used in the extraction. A bootstrapping procedure [32] is used to estimate both the statistical and systematic uncertainties. For multiplicity intervals where the result is consistent with zero, a limit is estimated at 95% confidence level (CL). This limit is obtained by making several variations of the default value $Y_{\mathrm{def}}(\Delta\varphi)$ of the per-trigger yield distribution, by adding random statistical and systematic fluctuations and extracting the ridge yield applying the procedure as given in Eq. (3). Gaussian fluctuations are randomly added bin-by-bin based on the statistical uncertainty. Systematic fluctuations are included by assuming that the $Y_s(\Delta\varphi)/Y_{\mathrm{def}}(\Delta\varphi)$ variation for each source of systematic uncertainty s has a common shift across $(\Delta\varphi, \Delta\eta)$ (not affecting the ridge yield) and a bin-by-bin component, taken to be Gaussian distributed and each variation corresponding to 1σ. It should be noted that the statistical uncertainties and the five sources of systematic uncertainty described below are all varied each time. The final uncertainty on Y^{ridge} is calculated as the standard deviation of the yield distribution obtained from a large number of these random variations.

The selection on the position of the primary vertex along the beam axis (z_{vtx}) is varied from $|z_{\mathrm{vtx}}| <$ 8 cm to 10 cm. The corresponding systematic uncertainty was found to be less than 5% depending on multiplicity. In order to estimate the bias due to the possible presence of jet-like correlations in $1.4 < |\Delta\eta| < 1.8$, the definition of the long-range region was changed to $1.5 < |\Delta\eta| < 1.8$. This change also estimates the effect of residual non-flow in the region in which the ridge yield is extracted. As the near-side ridge yield decreases towards low multiplicity, the relative contribution to the systematic uncertainty increases from 3% at high multiplicity to 22% at $\langle N_{\mathrm{ch}} \rangle = 15$, and dominates for lower multiplicity. Uncertainties related to track reconstruction were estimated by varying the required number of hits in the ITS layers allowing a more uniform detector acceptance but larger contributions from secondaries, resulting in 3–10% variation without a clear multiplicity dependence. Residual two-particle acceptance effects due to the finite accuracy of the event-mixing pair-acceptance correction, generally affecting the structure at long-range $\Delta\eta$, have been estimated to be around 4% on average. This contribution has been evaluated by adjusting the per-trigger yield with a $\Delta\varphi$-independent factor such that the away-side region is constant over $\Delta\eta$. As an additional check on the extraction of the associated yield, the $\Delta\varphi$ integration region is shifted with a resulting difference of about 1%. The total systematic uncertainty resulting from the bootstrapping procedure is around 15% at high multiplicities and 30% at low multiplicities.

Figure 1 presents the two-particle per-trigger yield for trigger and associated particle momentum of $1 < p_{\mathrm{T}} < 2\,\mathrm{GeV}/c$ in the multiplicity interval $32 < N_{\mathrm{ch}} \leq 37$. A prominent jet-fragmentation peak originating from correlations of particles from the fragmentation of the same parton is visible at $(\Delta\eta, \Delta\varphi) = (0,0)$. At $\Delta\varphi = \pi$, a broad away-side structure results from correlations of tracks from back-to-back jet-fragments that are spread over the entire $\Delta\eta$-region (as the parton–parton scattering center-of-mass frame is not the lab frame). The momentum region has been chosen such that these peaks are sufficiently narrow in $\Delta\varphi$, allowing one to extract the long-range ridge yield. At $|\Delta\eta| \gtrsim 1.4$ and $\Delta\varphi \approx 0$, the "ridge" structure is visible which was observed in previous measurements [47] and that in heavy-ion collisions is interpreted as a sign of collective expansion of the QGP medium.

Figure 2 shows the extracted ridge yield Y^{ridge} as a function of the average charged-particle multiplicity. The measured Y^{ridge} shows a strong multiplicity dependence, with an increasing trend towards higher multiplicity collisions. A non-zero Y^{ridge} is measured with good precision for events with $\langle N_{\mathrm{ch}} \rangle > 9$, significantly extending the low-multiplicity reach of previous measurements [35]. A limit, represented in

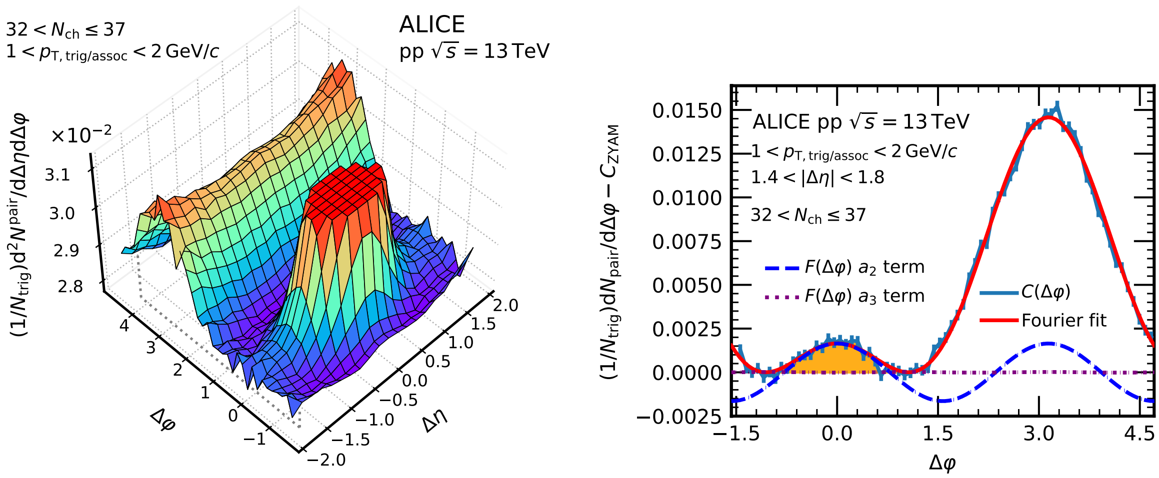

Figure 1: Two-particle per-trigger yield measured for charged track pairs with $1 < p_{\mathrm{T,trig}} < 2\,\mathrm{GeV}/c$ and $1 < p_{\mathrm{T,assoc}} < 2\,\mathrm{GeV}/c$ within the multiplicity range $32 < N_{\mathrm{ch}} \leq 37$. The jet fragmentation peak has been truncated to ensure a better visibility of the long-range structure. The right panel shows the zero-suppressed projection to $\Delta\varphi$ overlaid with $F(\Delta\varphi)$ (red line) and the area in which the ridge yield is extracted (shaded area). The blue and purple lines represent the second and third harmonic terms of $F(\Delta\varphi)$.

the figure by the black arrows, is computed at 95% CL for the three lowest multiplicity intervals ($\langle N_{\mathrm{ch}} \rangle < 9$) where no significant ridge yield was observed. The origin of the arrow corresponds to the threshold value of the ridge yield ($Y^{\mathrm{ridge}}_{\mathrm{CL}}$) for which 95% of the bootstrap distribution values are smaller than $Y^{\mathrm{ridge}}_{\mathrm{CL}}$. The results are compared with an analogous measurement performed by CMS (green markers) at the same center-of-mass energy. To allow for a direct comparison with the ALICE measurement, the x-axis of the CMS data was scaled by the ratio of the pseudorapidity acceptance of CMS and ALICE, which was estimated to be about 0.66 with negligible statistical uncertainty based on PYTHIA 8.3 simulations. The CMS result presents finite near-side yields for $\langle N_{\mathrm{ch}} \rangle \gtrsim 38$ and limits at 67% CL for smaller multiplicities. The two results are in good agreement at high multiplicities, where an accurate estimation of the ridge yields is available for both experiments. The comparison also includes CMS measurements at $\sqrt{s} = 7\,\mathrm{TeV}$. The measurement at $\sqrt{s} = 7\,\mathrm{TeV}$ has a smaller uncertainty at $\langle N_{\mathrm{ch}} \rangle \sim 32$ compared to the one at $\sqrt{s} = 13\,\mathrm{TeV}$ and also agrees with the ALICE results.

In Fig. 3, the result is compared to a recent measurement performed in $\mathrm{e^+e^-}$ collisions at $\sqrt{s} = 91\,\mathrm{GeV}$ in the thrust-axis reference frame using ALEPH archived data [32], where no evidence of long-range near-side correlations was observed. Due to the absence of beam remnants, the thrust axis provides an estimate of the longitudinal color field between the initially created $q\bar{q}$ pair and is therefore the sensible choice in $\mathrm{e^+e^-}$ collisions to search for collective effects. Similarly to the previous figure, in order to translate the ALEPH multiplicity into the ALICE acceptance range, a scaling factor is estimated with PYTHIA 8.3 events by counting the resulting particles in the acceptance ranges of both experiments ($|\eta| < 1.738$, $p_{\mathrm{T}} > 0.2\,\mathrm{GeV}/c$ in case of ALEPH). It is inherently difficult to compare the multiplicity in these two collision systems which have more than two orders of magnitude difference in collision energy as well as a different initial state leading to different flavour composition as well as multiplicity and momentum distributions. In order to give justice to these differences, this procedure was performed in both pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ and $\mathrm{e^+e^-}$ collisions at $\sqrt{s} = 91\,\mathrm{GeV}$ with resulting correction coefficients $c_{\mathrm{pp}} = 0.57$ and $c_{\mathrm{ee}} = 0.78$, respectively. The large difference between these two estimations reflects the different underlying mechanisms leading to multiplicity production in pp and $\mathrm{e^+e^-}$ collisions and is depicted by the horizontal uncertainty bars of the ALEPH ridge yields which are given as limits at 95% CL. In the multiplicity range 8 to 18 the yields in pp collisions are substantially above the ALEPH limit while outside this range the limits from $\mathrm{e^+e^-}$ collisions are above the pp measurement.

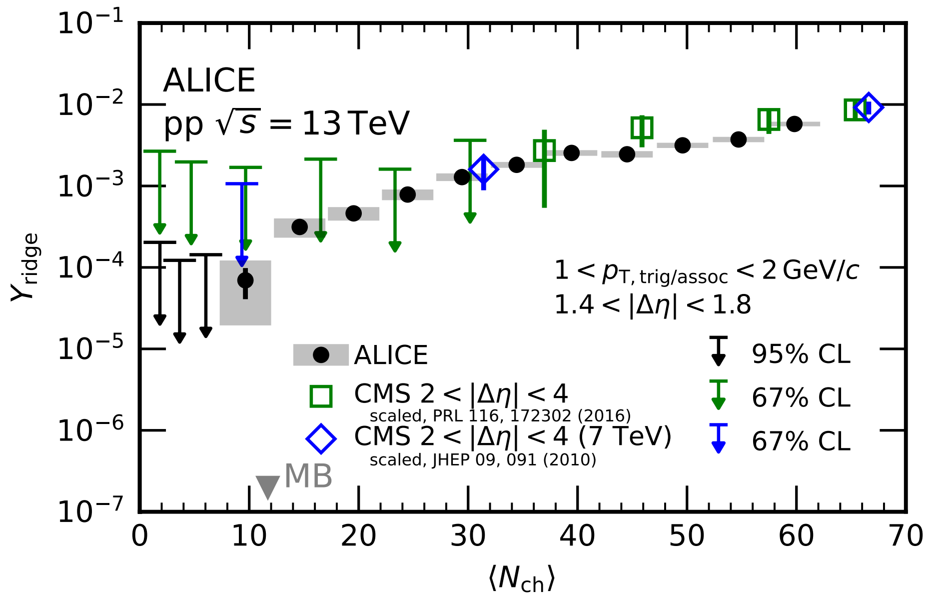

Figure 2: Ridge yield as a function of multiplicity. The black points correspond to the measurement presented in this Letter, while data from CMS [35] are drawn as green and blue markers. Vertical bars denote statistical uncertainties while systematic uncertainty is shown as shaded area. For both results, at low multiplicity where the lower uncertainty reaches zero, an upper limit is reported, which is drawn as a bar and arrow-down. Such points are given at 95% CL for the results from this Letter and at 67% for the results from CMS. The "MB" arrow indicates the multiplicity averaged over the entire considered multiplicity range.

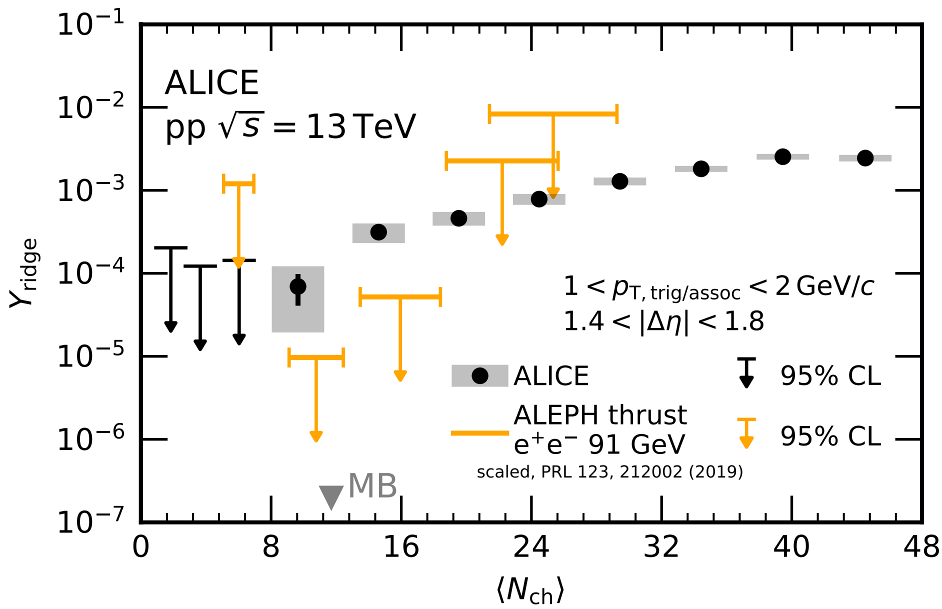

Figure 3: Ridge yield as a function of multiplicity, compared to the upper limits on the ridge yield in e^+e^- collisions. Vertical bars denote statistical uncertainties while systematic uncertainty is shown as shaded area. The orange limits represent the measurement in the thrust-axis reference frame with ALEPH [32]. The horizontal bars in the ALEPH points represent the uncertainty related to the multiplicity conversion from the ALEPH to the ALICE acceptance (see text). All limits are given at 95% CL.

In order to quantify this finding the significance of the result in pp collisions to be above the one in e^+e^- collisions is computed. The ALICE result is linearly interpolated between the two closest points

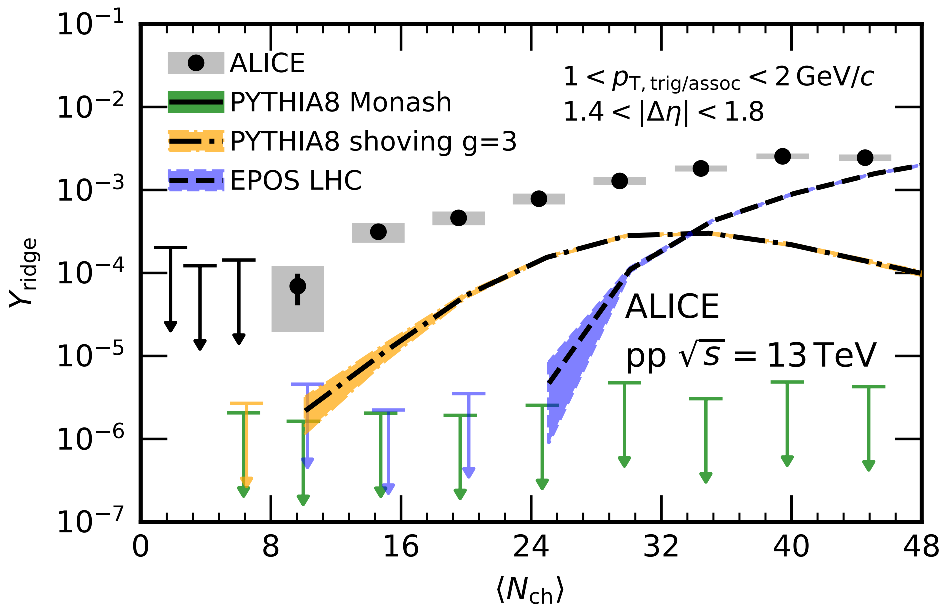

Figure 4: Ridge yield as a function of multiplicity compared to the predictions of PYTHIA 8.3 [38] with Monash tune [44] (green) and string shoving [48] (orange) as well as EPOS LHC simulations [40] (blue). Due to a larger jet fragmentation peak width in the simulations than in data, the yield is extracted within $2 < |\Delta\eta| < 4$ for the model calculations. A 95% CL is indicated for model calculations when the lower limit of statistical uncertainty is below zero. Some points are slightly displaced along the x-axis for better visualization. The band indicates the statistical uncertainty from the event generation and the extraction procedure.

to match the multiplicity. Statistical and systematic uncertainties contribute about equally and the results at different multiplicities are combined assuming the systematic uncertainty to be fully correlated across multiplicity intervals. The resulting significance of the pp measurement to be above the one in e^+e^- collisions is 3.8σ (using c_{pp}) and 5.0σ (using c_{ee}). Due to the precision of the ALEPH measurement, the multiplicity range which contributes mostly is between 8 and 18. Computing the significance separately in this range results in, for c_{pp}, a compatibility of 1.5σ and 3.2σ for the two ALEPH measurements within this multiplicity range, while c_{ee} yields 2.9σ and 4.4σ, respectively. This significant difference in the multiplicity range 8 to 18, where a near-side ridge is clearly present in pp collisions, suggests that the processes involved in e^+e^- annihilations do not contribute significantly to the emergence of long-range correlations in pp collisions.

In Fig. 4, the near-side yields are compared to the predictions of PYTHIA 8.3 with the Monash tune [44] and the string shoving tune ($g = 3$) [48], as well as EPOS LHC calculations. For the model calculations, a long-range definition of $2 < |\Delta\eta| < 4$ is used, as all of the models overestimate the width of the jet fragmentation peak. Under proper normalization, the choice of long-range definition does not affect the comparison, as the correlation is independent of $\Delta\eta$ [35] in this region, and the results can be directly compared. All models are found to underestimate the data in the examined multiplicity region, although PYTHIA with shoving and EPOS LHC do exhibit collective-like signals at $N_{ch} \gtrsim 10$ and $N_{ch} \gtrsim 24$, respectively. In contrast, the Monash tune as the no-ridge reference does not reproduce the near-side at all, and the yield remains zero across the entire multiplicity range. Only EPOS LHC describes quantitatively the magnitude of the yield at $\langle N_{ch} \rangle \geq 48$. These observations suggest that none of the models can fully capture the physics underlying the emergence of the near-side associated yield in low multiplicity pp collisions.

The high precision of this measurement allows one to draw quantitative comparisons between the ridge yield of a very small hadronic collision systems to the ridge yield measured in even simpler and well understood e^+e^- annihilations. The results presented in this Letter suggest that the ridge yield measured from a hadronic system of roughly equivalent multiplicity is non-zero and substantially larger than the limit observed in e^+e^- annihilations. Based on this, one can conclude that additional processes besides those in the e^+e^- annihilations must have role for the emergence of long-range correlations in pp collisions.

At the same time, the description of the ridge yields in well-established models is investigated. Calculations from three different models show that the ridge yield in the low multiplicity region in general is not reproduced. This suggests that the mechanisms for ridge yield production in very small hadronic collisions have not been understood and more theoretical work is needed.

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